A low progenitor mass for the magnetar SGR1900+14

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Magnetars are young neutron stars with extreme magnetic fields (B>10^{14}-10^{15} G) [1]. How these fields relate to the properties of their progenitor stars is not yet clearly established. However, from the few objects with initial mass estimates it has been suggested that a very massive progenitor star ($M_{prog} > 40M$) is required to produce a magnetar. Here we report that the initial progenitor star mass of the magnetar SGR 1900+14 was a factor of two lower than this limit, $M_{prog} = 17 \pm 1M$. Our results strongly contradict the prevalent hypothesis that only very massive stars can produce magnetars. Instead, we favour the "fossil-field" model as a possible explanation of the origin of these extreme magnetic fields.

It is still unclear how magnetars are formed. The current theoretical framework for magnetar

production requires that the core of a massive star has a very fast rotation speed in the first few seconds after it goes supernova (SN). If the rotation period is shorter than the convective timescale within the neutron star – about 1ms – a highly-efficient dynamo operates which boosts the magnetic field to 1000 times that of a ‘regular’ neutron star, and very rapidly slows the rotation period down to a few seconds [2]. However, recent stellar evolution calculations have shown that the cores of massive stars are substantially spun down as they enter the Red Supergiant (RSG) phase through magnetic braking between the stellar core and convective envelope [3]. Thus, the problem exists of how the core of a massive star can retain sufficient angular momentum through to the SN stage such that the post-SN core is able to jump-start the dynamo mechanism. It has been suggested that those stars with $M_{init} > 40M$ are able to lose a substantial fraction of their hydrogen-rich envelope while still on the main-sequence, allowing them to skip the RSG phase, and therefore avoid the severe spin-down of the core as the outer envelope expands and becomes convective [4].

Where magnetars have been associated with star-clusters it has been possible to estimate the initial mass of the progenitor empirically. As the magnetar phase is short, the SN that produced it must have occured recently ($< 10^4$yrs ago [5]). Consequently, by measuring the age of the star-cluster we can determine the age of the progenitor star when it went SN. Then, as a star’s lifetime is a strong function of its initial mass, we can estimate the initial mass of the magnetar’s progenitor. In the cases of the magnetars SGR 1806-20 and IGR J164710.2-455216, associated with the clusters Cl $1806 \quad 20$ and Westerlund 1 (Wd 1) respectively, it appears that the magnetar progenitors had initial masses $>40M$ [6–8]. These results are therefore consistent with the hypothesis that magnetars decend from the most massive stars.

There is a third magnetar, SGR $1900+14$, which can be used to test this hypothesis. It too is thought to belong to a cluster [9,10], though the cluster is poorly studied as high line-of-sight extinction makes it difficult to observe at optical wavelengths. So far, the best evidence for the association of the magnetar and star-cluster comes from the detection of an infrared ring around the source, analysis of which placed the magnetar at the same distance from Earth as the cluster [11].

To further investigate the nature of this cluster and accurately determine the progenitor mass of SGR1900+14, we obtained both imaging and spectroscopic observations of the cluster (see Fig. 1 and caption). The goal of our analysis is to determine the age of the cluster using its two bright RSG members, whilst also studying the cluster's fainter population to ensure that the assumption of coevality is sound. Our analysis method is described in detail in previous work (see SI Sect. 2). Briefly, we use the stellar spectra in order to determine effective temperatures, and, from the star's observed near-IR colours, the extinction. By measuring the red-shifts of the stellar spectra and comparing to the Galactic rotation curve we obtain kinematic distances. From the extinction, distance, and bolometric correction appropriate for the star's temperature, we then derive the intrinsic luminosities. In combination with stellar evolution models, these luminosities are then used as diagnostics of the cluster's age. The results of this analyis are presented in full in Sect. 2 of the SI.

In terms of the cluster's age, we find that the RSG luminosities are *uniquely* fit by the rotating stellar evolutionary models at Solar metallicity [12] for an age of 14 ± 1Myr (see Fig. 2). Analysis of the fainter stars indicate that the cluster is consistent with being a coeval starburst to within the

errors. No Wolf-Rayet stars are found, which would imply star formation within the last 8Myr, while we find relative numbers of hot/cool stars that are entirely consistent with the model predictions for a coeval 14Myr cluster (SI Sect. 3). As the age of the cluster is much greater than the lifetime of the magnetar ($< 10^4$yrs), we can now estimate the mass of the magnetar's progenitor by determining the mass of the most massive star that could still exist in a cluster of this age. Using the same stellar evolution models as above we find that the initial mass of the magnetar's progenitor was $M_{prog} = 17 \pm 1 M$ (Fig. 2). We show in SI Sect. 4 that *this estimate is insensitive to which set of evolutionary models is used.* Furthermore, we discount the possibility that the magnetar progenitor was a merger of two $17M$ stars as highly improbable (See SI Sect. 4.1).

How does this mass compare to other post-SN objects with progenitor mass estimates? In Table 1 we list all known young clusters associated with neutron stars. As well as the three clusters containing magnetars, we also list the two recent discoveries of clusters associated with Pulsar Wind Nebulae (PWNe) – Cl $1813 \quad 13$ [13,14], and RSGC1 [15,16]. Prior to our current result, it could be argued from these data that there is a connection between magnetic field strength B and progenitor mass. However, the inclusion of SGR 1900+14 – the object with the lowest progenitor mass of the sample, but whose magnetic field is as large as any other on the list – appears to end any notion of a relation between B and M_{prog}. As such, our result provides a strong challenge to the hypothesis that magnetars decend from very massive stars – specifically, those stars massive enough to avoid the RSG phase during their evolution. From our current understanding of stellar physics, it is not possible for a $17M$ star to shed enough of its hydrogen-rich envelope on the main-sequence to avoid the RSG phase [12]. Though close-binary interaction may shorten the duration of the RSG

phase [17], the companion would be visible as an optical/near-infrared counterpart to the magnetar. No evidence for a counterpart for any magnetar currently exists.

If magnetars can be produced from stars which will inevitably suffer core spin-down during their evolution, then perhaps stellar rotation, and in turn initial stellar mass, are not the primary factors in the production of extreme magnetic fields in neutron stars. An alternative theory to the dynamo mechanism is the 'fossil-field' scenario, whereby a seed B-field is inherited by a newly-born star from its natal molecular cloud (e.g. ref [18]). This explanation is preferred from studies of the energetics of SN remnants associated with magnetars, in which no evidence has been found for the extra energy boost provided by the neutron star's rapid spin-down (such as predicted by the dynamo scenario) [19]. However, we note that while a handful of massive stars have recently been observed to have magnetic field strengths of 10^3G [20,21], no current theory exists for how such fields evolve with the star or how they may be amplified by 12 orders of magnitude at the point of supernova.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Figure 1 High resolution image of the centre of the 1900+14 cluster. The image, taken in the H-band, shows the fainter stars close to the two bright RSGs at the centre of the cluster. We use the stellar identifications of [10]; where we resolve one of Vrba et al.'s objects into multiple components we sub-label them alphabetically. Images were taken on 23 August 2008 using laser guide star adaptive-optics assisted imaging with the Keck Near-Infrared Camera 2 (NIRC2). This was supplemented with wide-field imaging from the UKIDSS Galactic Plane survey [24]. We also obtained high-resolution spectroscopy of the two RSGs in the region of the CO bandhead feature at 2.293μm, as well as low-resolution K-band spectroscopy between 2-2.4μm of several of the fainter stars in the field, using the Keck Near-Infrared Spectrograph (NIRSPEC) on 23 June 2008. We employed standard reduction techniques for both sets of data (see Supplementary Information (SI) Section 1).

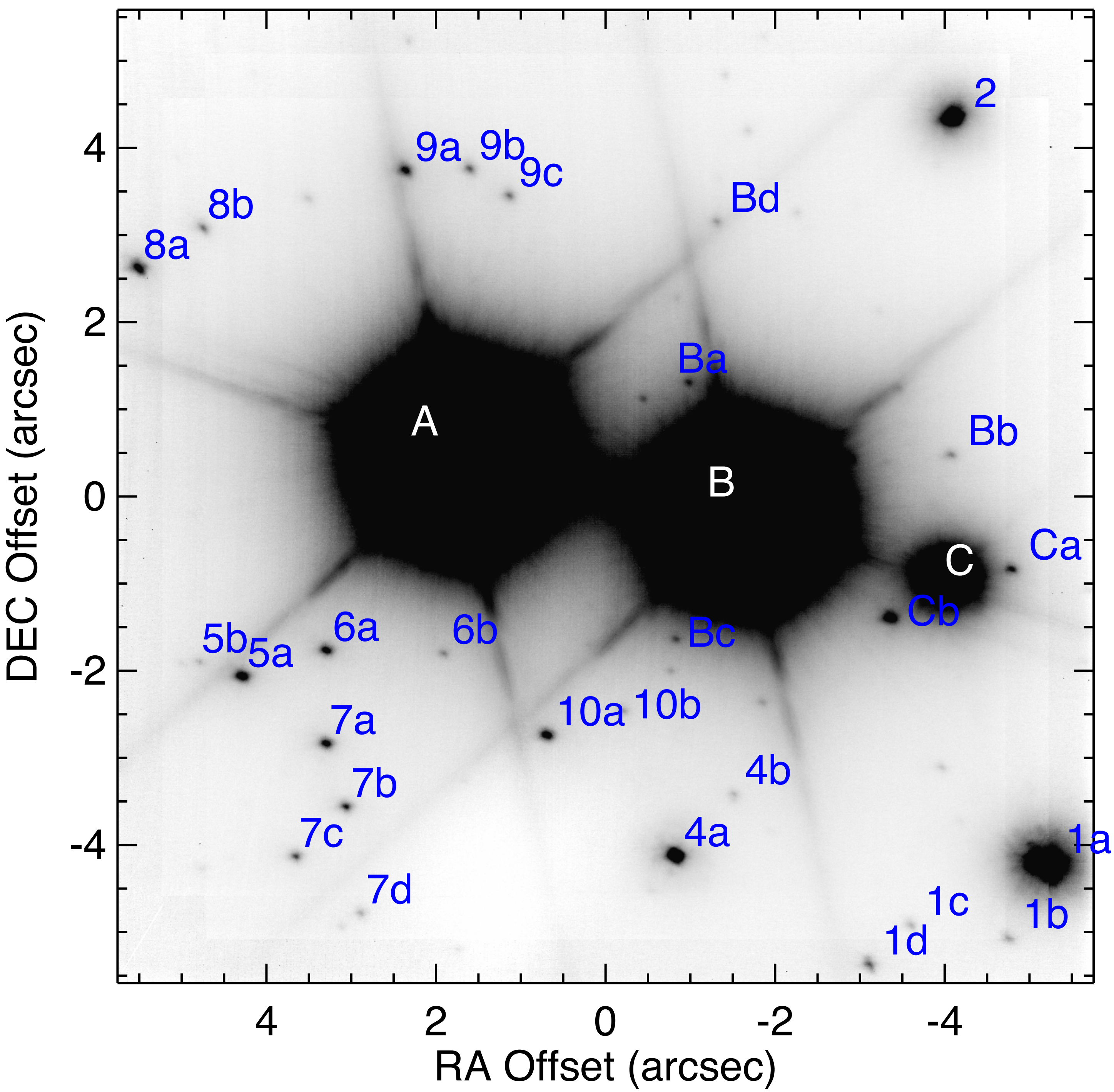
Figure 2 The mass of the most massive pre-supernova star in a cluster of a given age. The figure shows the minimum and maximum luminosities of Red Supergiants (RSGs) in a coeval cluster, as a function of cluster age, calculated using the Geneva rotating models at Solar metallicity[12]. The initial masses of the stars in the RSG phase are indicated by the data labels. The red arrows indicate the range of RSG luminosities we observe in Cl 1900+14, ±1 . We can say that the cluster *cannot* be younger than 10.5Myr, as the least luminous RSG in such a cluster would be brighter than the brightest RSG in Cl 1900+14. Similarly, we can place an upper limit to Cl 1900+14's age of 18.5Myr from the luminosity of the faintest RSG in the cluster. From the RSG luminosity range we

observe in the cluster, we can constrain the age to 14 ± 1 Myr. Using the same stellar models, we can determine the maximum mass of a star that would still exist in a cluster this age. Assuming that the age of the magnetar is negligable compared to the age of the cluster, we find a magnetar progenitor mass of $17 \pm 1 M$. Using the more generous upper and lower limits on the cluster age, we find $M_{prog} = 17^{+5}_{4} M$.

Table 1: Post-supernova objects with known progenitor masses.

Object [+ cluster]	M_{prog}/M	Remnant	B (10^{14}G)	Ref.
SGR 1806-20	48^{+20}_{8}	Magnetar	2-8	7, 22
CXO J164710.2-455216 [Wd 1]	40 ± 5	Magnetar	<1.5	8
IGR J18135-1751 [Cl 1813-18]	20-30	Pulsar Wind Nebula	1[4]	13, 14
AX J1838-0655 [RSGC1]	18 ± 2	Pulsar Wind Nebula	0.02	15, 16
SGR 1900+14	17 ± 1	Magnetar	2-8	This work, 23

[4]This value is highly uncertain due to the lack of a measured period and spin-down rate, and may be an order of magnitude lower.



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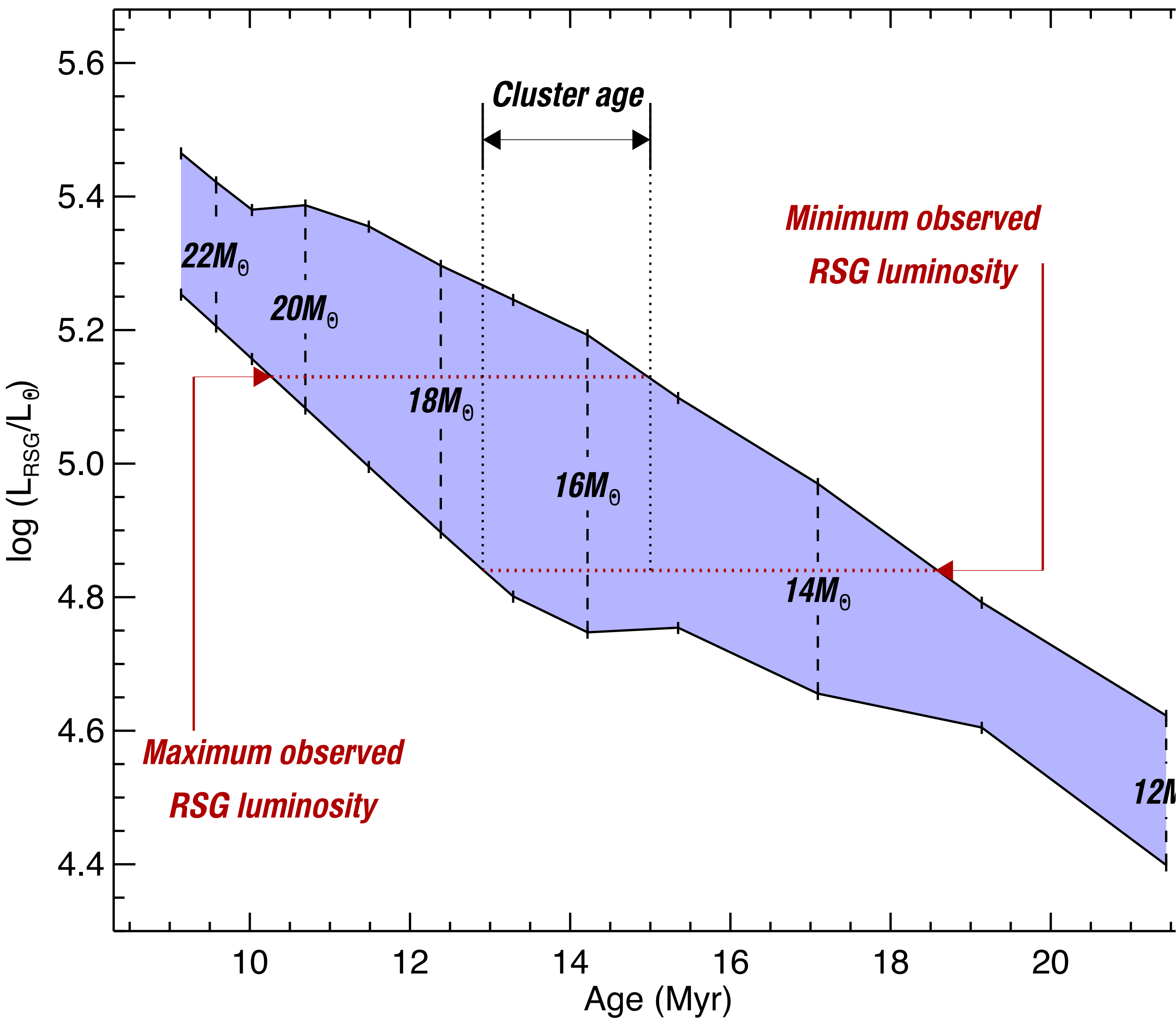

Cluster age
Minimum observed
RSG luminosity
Maximum observed
RSG luminosity
22M⊙
20M⊙
18M⊙
16M⊙
14M⊙
12M
log (L_RSG/L⊙)
Age (Myr)
5.6
5.4
5.2
5.0
4.8
4.6
4.4
10
12
14
16
18
20